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Highly Operable Propulsion for Reusable Launch Vehicle Applications

Michael Marlow*
Aerojet, Sacramento, CA

ABSTRACT

A wide variety of reusable launch vehicle concepts for placing various payloads into low earth orbit are currently being evaluated for potential civil, commercial and military applications. This recent interest is being driven by a desire to achieve reduced payload launch costs and, in some cases, very rapid response capability. In most of these cases, the general requirements of the main propulsion system are similar: a high level of operational availability with minimal operational support activity. Consequently, evaluation of traditional expendable rocket engines as candidates for reusable applications has begun, with an emphasis on understanding whether or not a given engine's operating characteristics are inherently more reusable than another.

In support of a planned program to demonstrate a low cost, rapid response reusable launch vehicle, several existing rocket engines were evaluated for feasibility to meet the requirements of a sub-scale reusable launch vehicle demonstrator. Critical propulsion characteristics were defined based on the demonstration objectives of the overall program. Potential candidate engines were selected and then evaluated against these critical propulsion characteristics, and a comparative assessment of each engine's ability to satisfy each critical characteristic was generated. Finally, a reference engine was designated along with a reference demonstrator vehicle concept. This vehicle concept was evaluated for its feasibility to satisfy the reusable launch vehicle demonstrator program objectives, and determined to meet the stated goals with residual capability for possible later applications.

INTRODUCTION

To date, a reusable launch vehicle (RLV) that is low cost, enables short turnaround times and requires minimal ground operations between flights has never been demonstrated. Therefore, the extent to which these RLV goals can be truly realized is unknown. Consequently there is an understandable reluctance to initiate major vehicle development efforts without first gathering test data that helps identify and quantify the extent of the potential benefits. One low cost approach being considered to provide these data is the Reusable Access to Space Technology (RAS-T) Program. The objective of this program is to develop a sub-scale flight demonstrator that makes extensive use of existing hardware - including main propulsion - to demonstrate reusable launch vehicle operations in a manner that is traceable and scalable to future operational RLV concepts.

A space launch vehicle represents a highly integrated group of systems all working together to deliver a payload to its desired orbit. Examples of major vehicle systems include airframe, thermal protection system, avionics, propulsion, etc. In a reusable launch vehicle, each of these systems contributes to the operational turnaround demands of the overall vehicle. Over 20 years of experience with the U.S. Space Transportation System (STS) reveals that main propulsion contributes to a significant portion of the overall ground operations activity, schedule and cost^{1,2}. Main propulsion also represents a significant portion of the preflight activities associated with expendable launch vehicles. Therefore, if significant improvements to operational support activities are expected for any future reusable launch vehicle, then demonstration of the main propulsion system must be considered as a key focus area.

CRITICAL PROPULSION CHARACTERISTICS

The RAS-T Program will develop and test a sub-scale RLV demonstrator that is scalable and traceable to a military space plane (MSP)

* Engineering Specialist, Member AIAA

concept that is currently under study. The MSP concept is based on a reusable two-stage to orbit (TSTO) vehicle that will take-off vertically and land horizontally. The first and second stages are winged for fly-back capability. This concept is illustrated in Figure 1.

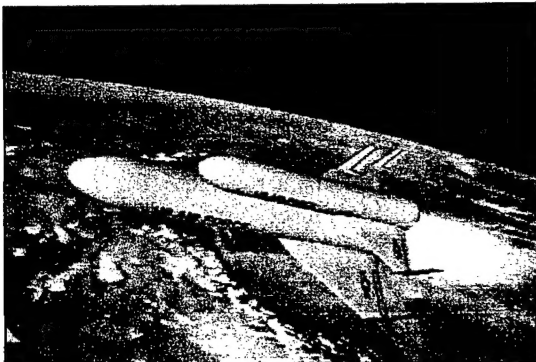


Figure 1. Operational Reusable MSP Concept

In order to reduce the cost of the RAS-T demonstrator program, only one of the stages will be developed and tested, but in a test program that will allow demonstration of the operational characteristics of key systems applicable to both stages. In addition, this RLV demonstrator will be sub-scale to further reduce cost.

Based on this operational MSP concept a baseline set of technical and programmatic requirements were established for the RAS-T demonstrator vehicle, with an emphasis placed on traceability and scalability to the MSP. For example, vehicle mass was defined based on payload capability demonstration objectives; main propulsion thrust class was defined based on total vehicle/payload mass; LOX/hydrocarbon was selected as an operationally representative propellant combination; and vehicle sortie rate and quantities were established as RLV capability demonstration goals.

Based on these and other program requirements that were developed, a corresponding set of key characteristics for the demonstrator vehicle main propulsion were also established. These critical propulsion characteristics, shown in Table 1, are grouped into three primary categories of interest: operability, performance and cost.

Since the primary objective of the overall program is to demonstrate operability of a reusable launch vehicle, the characteristics that fall under this category were considered to be of greatest importance. However, performance and cost are always important factors that directly influence propulsion selection for a launch vehicle.

CANDIDATE ENGINES

For a low cost demonstrator program, the use of existing hardware is highly desirable wherever possible, provided the objective of demonstrating RLV operability is not unduly compromised. This constraint applies to all major systems on the demonstrator, including the main propulsion. Therefore, only existing or readily available engines were considered viable candidates for full evaluation.

The candidate engines initially selected for evaluation are shown in Figure 2. In order to preserve traceability to operational booster concepts, only LOX/hydrocarbon engines were considered as candidates. Due to demonstration vehicle mass fraction requirements, only pump fed engines were considered, although a wide range of thrusts were considered, enabling either

Operability – the Primary Criterion

- Inherently reusable
- Demonstrated long life & multiple start capability
- Rapid turn-around between engine firings
- Inherent high reliability and catastrophic reliability
- Thrust class allowing multi-engine redundancy for engine-out mission capability
- Propellants and ground ops representative of / traceable to operational RLV

Performance

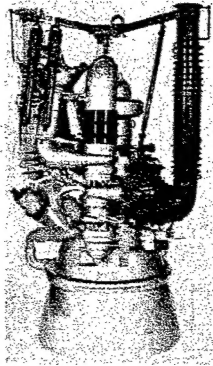
- High I_{sp} and high sea level thrust-to-weight for maximum vehicle benefits
- Throttling for mission flexibility and engine out mission capability
- Gimbal capability
- In-flight restart capability for mission flexibility

Cost

- Existing or readily available engine inventory
- Low cost risk
 - Reusable propulsion experience
 - Engine adaptation experience
- Engine adaptable to wide variety of vehicle configurations

Table 1. Critical Propulsion Characteristics

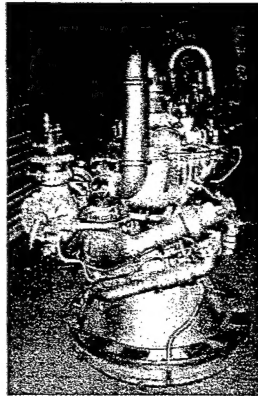
Russian Built Engines



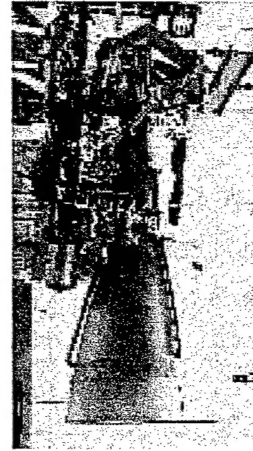
RD-0125
49,000 lbf



RD-0242
20,900 lbf



NK-39
69,000 lbf

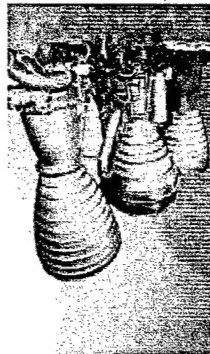


NK-33
342,100 lbf

U.S. Built Engines



Fastrac
60,000 lbf



MA-5A
Sustainer
60,500 lbf



RS-27A
200,000 lbf

Note: Thrust values shown are at sea level.

Figure 2. Candidate Engines Considered for Initial Evaluation

single engine or multi-engine vehicle configurations.

A summary of the key characteristics for each candidate engine is provided in Table 2.

CRITICAL PROPULSION CHARACTERISTICS COMPARISON

Selected candidate engines were evaluated for applicability to this RLV demonstrator program using the defined critical propulsion

characteristics. This evaluation was done on a qualitative basis, comparing each engine's given characteristic relative to each of the other engines. This approach could eventually be applied as a quantitative comparison, by assigning numerical weights to each desired characteristic (based on importance), then assigning a numerical rank for each candidate engine's actual characteristic, multiplying each engine's rank times the weight of that characteristic, and then summing and comparing total scores. However, at this early stage in the

Candidate Engine	Thrust, lbf (SL)	Isp, sec (SL)	Weight, lbf	Thrust-to-Weight	Combustion Cycle	Propellants	Availability
U.S.							
Fastrac	48,082 (15:1 nozzle)	236 (15:1 nozzle)	1,870 (30:1 nozzle)	26	Gas Generator	LOX/RP-1	Never in production, but designed for low cost
MA-5A Sustainer	60,500	220	1,035	58	Gas Generator	LOX/RP-1	Out of production
RS-27A	200,000	254	2,528	79	Gas Generator	LOX/RP-1	In production
Russian							
RD-0125	49,077	283	809 (at 40:1 Area Ratio)	61	Ox Rich Staged Combustion	LOX/RP-1	Modification to production hardware
RD-0242	20,876	289	303 (at 40:1 Area Ratio)	69	Ox Rich Staged Combustion	LOX/RP-1	Modification to hardware in stores
NK-39	68,990	270	1,290	53	Ox Rich Staged Combustion	LOX/RP-1	Limited number of engines with correct area ratio
NK-33	342,099	299	3,200	107	Ox Rich Staged Combustion	LOX/RP-1	Many engines now available

Table 2. Key Engine Characteristics Summary

program, where the demonstrator vehicle concept, requirements and characteristics are still tentative, a qualitative comparison was determined to be adequate.

Results of the engine comparison are provided in Table 3. Note that during the initial evaluation, three of the candidate engines were removed from further consideration and are not included in the table:

- The RD-0242 was removed because the thrust class was determined to be too small for the demonstrator vehicle concept that was evolved.
- The MA-5A was removed due to its poor performance relative to other available engines, and lack of availability.
- The Fastrac engine was removed due to its very poor performance relative to other available engines.

By removing these three engines, Table 3 can be viewed as a comparison of two separate thrust classes of engines: the left two engines fall in the under 100K lbf thrust range, while the right two engines are well over the 100K lbf thrust range.

Operability

Comparatively speaking, an ox-rich cycle engine, with its clean preburner combustion exhaust, offers an advantage over a soot-producing fuel rich gas generator cycle engine in reusable engine applications: no need for the added ground crew, support equipment and operational activities associated with removing soot deposits after each engine firing. This engine-cleaning requirement is a comparative disadvantage for the RS-27A. All of the other candidate engines are ox-rich staged combustion cycle engines.

Operability - the Primary Criterion	RD-0125 49K lbf	NK-39 69K lbf	NK-33 342K lbf	RS-27A 200K lbf	Comments
Inherently reusable					RS-27A fuel rich GG cycle poor for reuse.
Demonstrated long life & multiple start capability					RS-27A only has single-use heritage.
Rapid turn-around between engine firings					RS-27A fuel rich GG cycle sooting ops issues. RD-0125 engine start w/o prechill and 51 hour wet hold capability, cold gas spin start.
Inherent high reliability and catastrophic reliability					All engines have good heritage. RS-27A has an established flight record.
Thrust class allowing multi-engine redundancy for engine out mission capability					High thrust class engines too large for multi-engine RSAT vehicle configuration.
Propellants and ground ops representative of / traceable to MSP operations					RS-27A operations not applicable to MSP.
Performance					
High Isp and high sea level thrust-to-weight for maximum vehicle design benefits					RS-27A has good thrust-to-weight, but low Isp. RD-0125 & NK-33 provide outstanding overall performance.
Throttling for mission flexibility and engine out mission capability					RS-27A is currently non-throttling, but may be adapted.
In-flight restart capability for mission flexibility					RS-27A is non-restarting.
Gimbal capability					Engines easily adapted for gimbaling.
Cost					
Existing or readily available engine inventory					All candidate engines are readily available
Reusable propulsion experience					"Americanized" NK-33 reuseability demonstrated. RS-27A historical experience: SSME requires extensive turn-around ops.
Engine adaptation experience					"Americanized" NK-33 multi-vehicle adaptation demonstrated. RD-0125 adaptation experience heritage extensive. RS-27A heritage limited to Delta.
Engine adaptable to wide variety of vehicle configurations					High thrust limits minimum vehicle weight, non-throttling even more so. RS-27A poor for vehicle packaging.



Excellent



Good



Fair



Poor

Table 3. Critical Propulsion Characteristics Comparison

Another drawback of the fuel-rich gas generator cycle's sooting is the impact that it has on response time. The ability to demonstrate rapid response and high sortie-rate capability is limited by the need to perform soot-cleaning activities between flights. In contrast, the RD-0125, with its cold gas spin start rather than the pyrotechnic start cartridge used by the other engines, requires one less consumable to be replaced after each flight. This further reduces operations and improves responsiveness and operational availability. It is important to note here that one of the primary goals of the RAS-T Program is to demonstrate the capability to turn a vehicle around within hours. Therefore, any engine characteristic that effects turnaround capability is critical.

All of the candidate engines have experience with multiple hot fire tests. However, all of the ox-rich staged combustion cycle engines have been subjected to test programs designed to demonstrate multiple starts and long-duration operational capability. This demonstrated reusability provides two benefits: it allows early engine selection based on actual test data, and allows early demonstrator mission planning based on high confidence engine reuse experience. It also precludes the need to add life demonstration testing to the demonstrator program.

Additional comparative differences in the area of operability are described in Table 3.

Performance

The RAS-T demonstrator vehicle concept is based on vertical takeoff. Therefore, high sea level thrust capability is a desirable engine characteristic. In addition, as with most rocket engine applications, high engine efficiency and high thrust-to-weight are also important factors for selection. Generally speaking, an ox-rich staged combustion (closed cycle) engine provides superior I_{sp} over a comparable gas generator (open cycle) engine. The only candidate engine here that uses a gas generator cycle is the RS-27A, a comparative disadvantage, although this disadvantage is offset somewhat by the good thrust-to-weight that is realized by gas generator cycle engines in this thrust class.

Of the remaining engines, the NK-33 offers outstanding I_{sp} and thrust-to-weight with the RD-0125 being the next best of the candidate engines.

Engine throttling capability allows increased mission flexibility. All of the candidate engines are throttling except for the RS-27A. However, gas generator cycle engines are not inherently non-throttling, and this engine may be adaptable for throttling with redesigns of the limiting engine components.

One important note regarding throttling: when operating an engine in the throttle-back condition, life-limiting stresses are reduced and overall engine operating life can be increased, provided the engine can also deliver a corresponding number of engine starts. Significant increases to engine life and engine starts have been demonstrated with all of the ox-rich staged combustion engine candidates in reduced throttle operating conditions. This provides even further operational availability for the demonstrator vehicle.

Additional comparative differences in the other areas of performance are described in Table 3.

Cost

Rather than attempting to generate ROM cost estimates for each candidate engine based on the required non-recurring and recurring activities necessary to adapt each unique engine to this demonstrator program, the critical characteristics identified in the area of cost were focused instead on key cost-affecting attributes of the engines.

All of the engines shown in Table 3 are either existing assets or readily available. This precludes the need for cost prohibitive propulsion development expenses, other than those required to adapt the engine to the vehicle.

The NK-33 has already been "Americanized" – selected features have been modified to enhance the reusability of this engine – allowing immediate application of a well-characterized reusable design³.

The NK-39 is a smaller version of the NK-33, and as such could be easily modified (based on the NK-33) for enhanced reusability.

The RD-0125 is a single chamber adaptation of the highly successful RD-0124 engine, which itself was developed to replace the RD-0110 as the third stage engine for the Soyuz-2 launch vehicle.

The RS-27A engine application has only included the Delta II/III launch vehicle. Consequently, demonstrated adaptability and reusability heritage is limited.

Reference Engine Selection

Although the RD-0125 had a higher overall comparative score than the NK-39, the NK-39 was selected as the reference engine for the reference vehicle concept for RAS-T, primarily due to availability and thrust class. NK-39 availability is excellent, with adequate quantities of existing assets available to meet anticipated demonstrator program needs. At the time of this selection, a multi-engine vehicle configuration was considered to be a high priority, in order to demonstrate engine-out capability. The NK-39 thrust level supports this multi-engine configuration. Finally, the reference engine is simply being used as a baseline against which other options will be evaluated during the follow-on study phase of the program. Therefore, selection of a reference engine at this point in the program is for study purposes only.

The reference demonstrator vehicle concept, shown in Figure 3, was compared against a defined set of demonstrator program objectives, to ensure that they could be satisfied by this concept. Not only was the reference vehicle concept acceptable for demonstrating the program goals, it also was determined to have residual capabilities that may be useful for follow-on test purposes in areas other than operational demonstration. It is also being used as a baseline against which alternate vehicle concepts are being evaluated. Ultimately, other



Figure 3. RAS-T Demonstrator Vehicle Concept

industry concepts will be studied and the best solution will be selected for development and demonstration. These activities will begin in late GFY 2003, with a goal of initiating flight test demonstrations of the sub-scale operations demonstrator RLV in GFY 2007.

PREFERRED ENGINE COMBUSTION CYCLE IDENTIFIED

All of the candidate engines available for consideration for this program fall under one of two combustion cycles: gas generator or staged combustion. Both engine cycles are depicted in Figure 4.

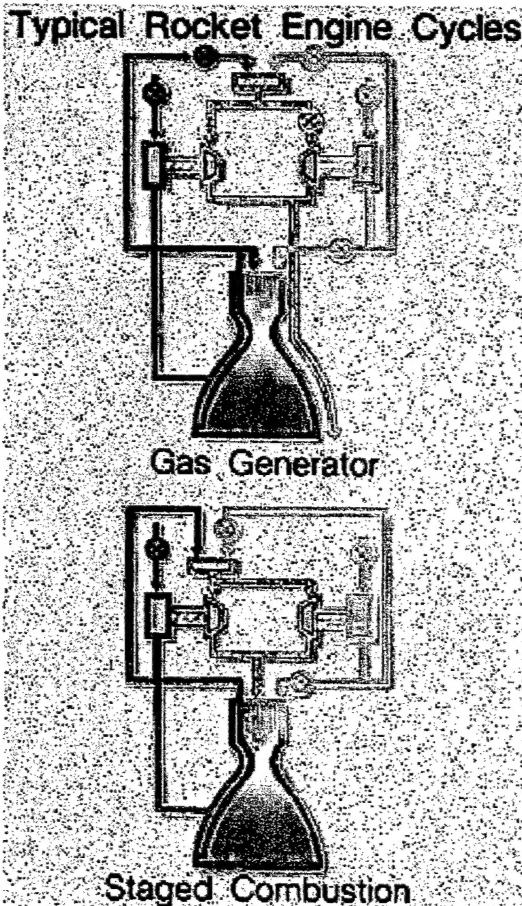


Figure 4. Engine Combustion Cycle Comparison

LOX/kerosene gas generator cycle engines operate the gas generator fuel rich, exhausting soot-laden combustion products through a turbine to drive the engine's pumps. Typically this soot build-up must be cleaned out of the gas generator between each engine hot firing. And it is the lower operating pressures that represent lost potential performance for the engine.

LOX/kerosene staged combustion engines operate the preburner ox-rich, producing a very clean combustion exhaust that doesn't require cleaning between each engine hot firing. Additionally, all of the warm GOX from the preburner is directed through the turbine and into the main combustion chamber. Higher preburner operating pressures and higher main combustion chamber pressures result in higher engine thrust and efficiency. For these reasons, all future LOX/hydrocarbon booster engine development programs in the U.S. are based on the ox-rich staged combustion cycle.

From the operability, performance and cost comparisons described previously, it is apparent that the staged combustion cycle is better suited for reusable launch vehicle applications. The operational and performance benefits leverage directly to vehicle cost, flight program cost and engine operational support costs. Moreover, all operational lessons to be learned from a demonstrator program that uses an ox-rich staged combustion cycle engine will be directly applicable to future U.S. development efforts for both U.S. booster engines as well as the MSP.

Ox-rich Staged Combustion Engine Availability

All future U.S. planned LOX/hydrocarbon engines are based on the ox-rich staged combustion cycle. However, none are currently available. Several U.S. LOX/hydrocarbon engines are currently available, but all are based on the gas generator cycle, and poorly suited for reusable operations capability demonstration.

The Russians have been using ox-rich staged combustion LOX/hydrocarbon engines since the 1960s. They have extensive experience applying this combustion cycle to a wide variety of thrust class engines. All of the candidate Russian engines considered under this study have extensive testing experience with demonstrated multiple-start and long life operation – directly applicable to RAS-T objectives for operational demonstration.

Russian Engine Availability

Extensive historical experience and precedence shows that Russian engines are readily available to the U.S., for both commercial and U.S. Government programs. In particular, Aerojet has a consistent track record in importing Russian engines. Over a period of more than a decade, Aerojet has imported over 50 Russian engines into the U.S. Thrust classes have ranged from fractional-pound to half-million pounds. Propellants have included LOX/hydrogen, LOX/hydrocarbon, storables and electric. A summary of successful U.S. applications by Aerojet is provided in Table 4.

Operational demonstration and operational "lessons learned" are the primary objectives of the RAS-T Program, and are not restricted with Russian engine usage. By treating the Russian engine as a simple buy item, this avoids technical data rights restriction issues and enables operational demonstration without

operational use restrictions – the approach currently being taken for the NK-39, the RAS-T reference engine.

Russian Engine	Program	Comments
NK-33	EELV; Kistler; J-I Upgrade	Engine imported to & tested in U.S.
NK-43	EELV; Kistler	Engine imported to U.S.
RD-0120	X-33	Engine imported to U.S.
D-57	X-33	Engine imported to U.S.
ZhRD-400N	Satprop Program	Engine imported to & tested in U.S.
Hall Effect	STEX	Engine imported to U.S.

Table 4. U.S. Programs with Russian Engines

Operability

- Ox-rich staged combustion cycle
- Dry engine start enables rapid call-up (2-4 hour goal)
 - No prechill improves launch readiness and eliminates RP-1 freezing during launch delays
- Rapid engine turnaround (4-8 hour goal)
 - No propellant circuit flushing
 - Ops-based consumables (igniters & start cartridge only)
- Very well characterized long life, multi-start & reliability
 - 0.9994 multi-engine RAS-T mission reliability
 - 0.9995 catastrophic reliability
- Correct thrust class for multi-engine vehicle
 - Enables engine out mission capability

Performance

- Excellent I_{sp} & good thrust-to-weight
- Throttling and gimbaling capability
- In-flight restart capability - enables mission / trajectory flexibility

Cost

- Existing inventory available
 - Sufficient quantity for RAS-T Program
- Adapting for reusable U.S. application is very low cost risk
 - Nearly identical to successful "Americanized" NK-33

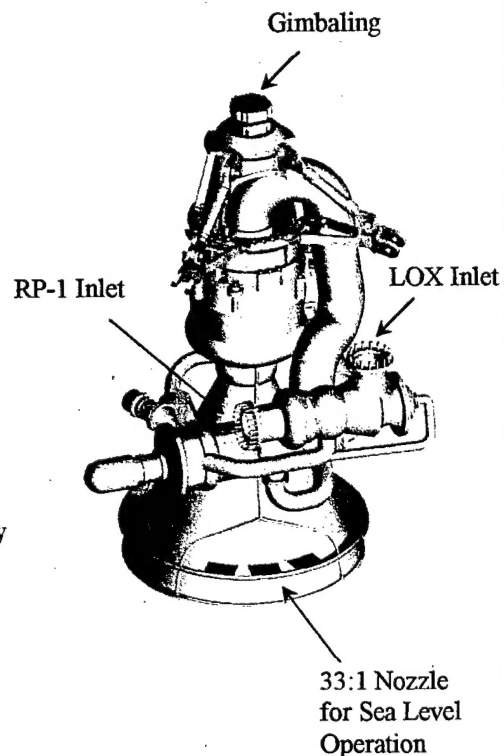


Figure 5. NK-39 Reference Engine Characteristics

Comparison to NK-39 Reference Engine

Operability

- Also ox-rich staged combustion cycle engine
- Also dry engine start (no prechill), but additionally
 - 51 hour wet on-pad hold capability
- Comparable call-up & turnaround times, but additionally
 - GN2 spin start precludes start cartridge reloading
- Excellent long life, multi-start & reliability heritage
 - 0.994 multi-engine RAS-T mission reliability
 - 0.999 catastrophic reliability
- Similar thrust class preserves multi-engine vehicle

Performance

- Outstanding I_{sp} & slightly higher thrust-to-weight
- Also throttling & gimbaling, in-flight restart capability

Cost

- CADB track record with U.S. has been excellent
 - Extensive engine adaptation experience
- Leverages successful uprated Soyuz third stage engine program

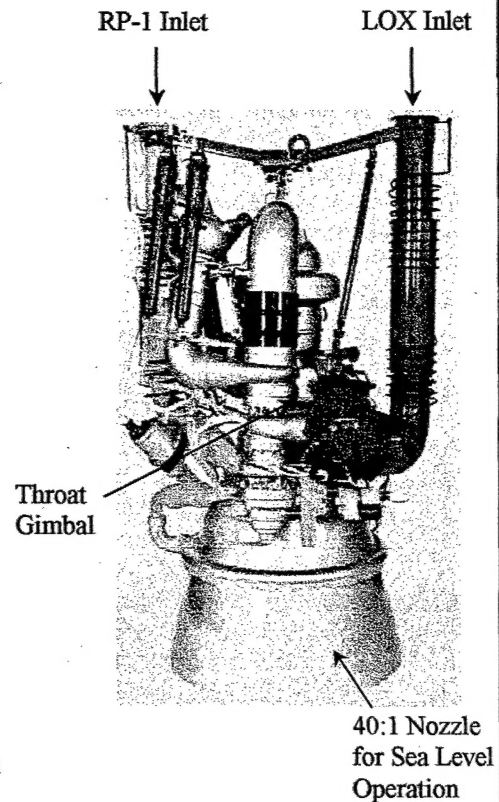


Figure 6. RD-0125 Engine Characteristics

Comparison to NK-39 Reference Engine

Operability

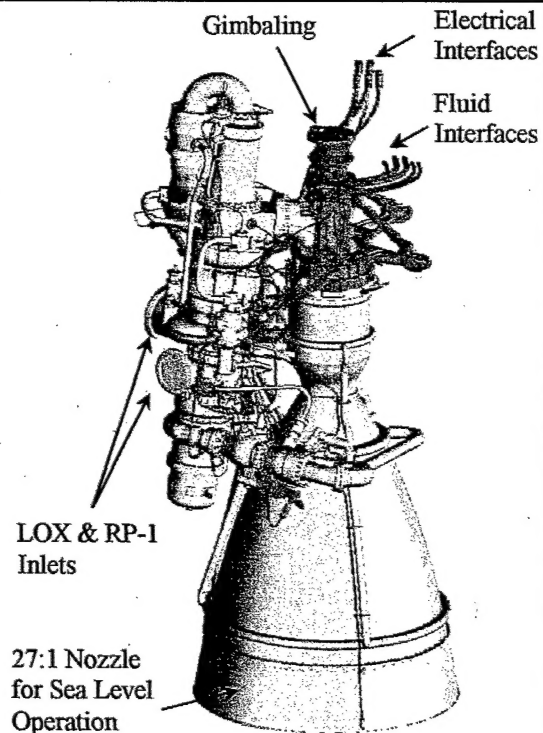
- Also ox-rich staged combustion cycle engine
- Comparable call-up & turnaround times
- Very well characterized long life, multi-start & reliability
 - 0.998 mission reliability
 - 0.9998 catastrophic reliability
- Significantly higher thrust class
 - Eliminates multi-engine vehicle capability, but...
 - Allows increased engine life by throttling down

Performance

- Outstanding I_{sp} & outstanding thrust-to-weight
- Also throttling, gimbaling, in-flight restart capability

Cost

- Already adapted for reuse and U.S. interfaces
 - Operability & performance already demonstrated
- Extensive existing inventory available
 - 38 engines available - in the U.S.



Aerojet Engine Modifications Shown in Red

Figure 7. NK-33 Engine Characteristics

CANDIDATE ENGINE DESCRIPTIONS

A brief description of each candidate Russian engine is provided in Figures 5, 6 and 7, including a comparison of each engine relative to the designated reference engine, the NK-39. Engine characteristics are grouped under the same categories as done for the comparison study: operability, performance and cost.

CONCLUSIONS

A low-cost approach to evaluating the potential operational capabilities of a MSP is to combine key first and second stage demonstration objectives in a single, sub-scale demonstrator vehicle. To ensure that the results are traceable and scalable to the MSP, those vehicle systems that have the greatest impact on operations, including main propulsion, should be as closely based on the MSP vision vehicle as possible, while still taking maximum advantage of available or existing hardware. This is the approach that is being taken with the RAS-T Program.

Ox-rich staged combustion cycle engines are the best choice for reusable launch vehicle applications in general, and military space plane applications in particular. The clean-burning ox-rich cycle avoids the engine cleaning activities that are required by a gas generator cycle engine, and the staged combustion cycle provides superior performance. By not having to perform engine-cleaning activities between each flight, turnaround time is improved - a key advantage for a rapid response MSP - and ground support crew and equipment demands are lessened, allowing for reduced operating costs and improved operational availability.

The use of an existing ox-rich staged combustion engine in a MSP demonstrator program provides an excellent opportunity for "spiral development." It allows the U.S. to build on already-established capabilities, while following a low-risk development path that is scalable and traceable to future U.S. development efforts for both U.S. booster engines as well as the MSP.

Three ox-rich staged combustion engines have been identified as excellent candidates and currently available for use on the RAS-T Program:

- NK-39 - Existing engines built and available, easily "Americanized" for improved reusability (very similar to the NK-33), and very well characterized long life and reusability

- RD-0125 - Thrust class comparable to the NK-39, but provides improved operability, improved performance, and improved life and reusability
- NK-33 - Provides the best performance of any candidate engine, has very well characterized long life and reusability, and a reusable "Americanized" configuration is complete and qualified

All three engines studied offer the best chance for helping an operational demonstrator vehicle achieve its goals of rapid response and low cost reusability.

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